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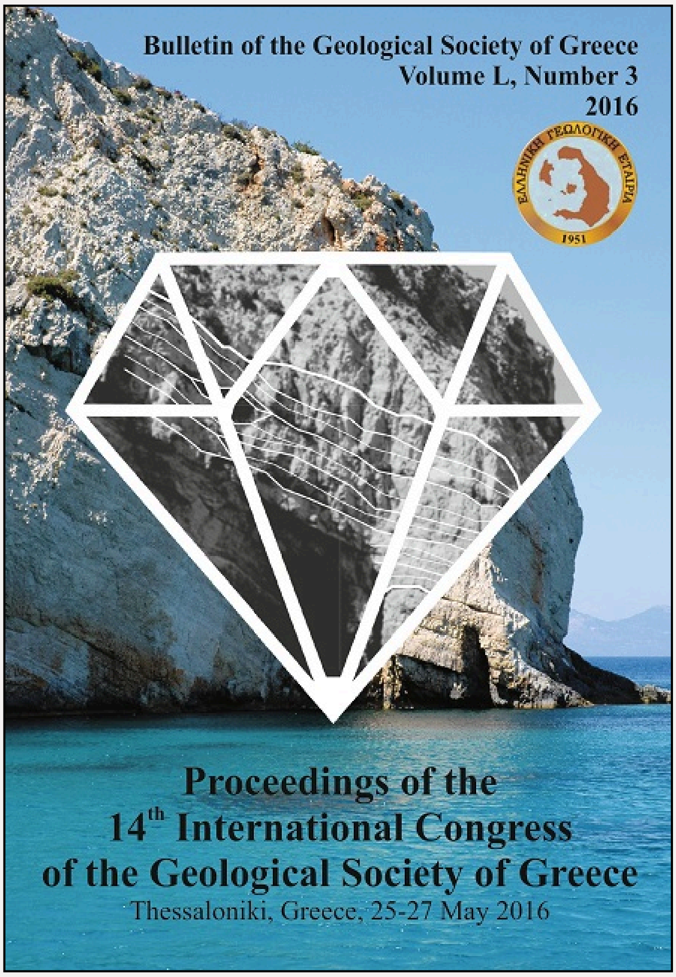


# UNDERSTANDING THE PHYSICS OF KAPPA (K0): INSIGHTS FROM THE EUROSEISTEST NETWORK

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# UNDERSTANDING THE PHYSICS OF KAPPA ($K_0$): INSIGHTS FROM THE EUROSEISTEST NETWORK

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**Abstract**

*In this study we estimate the spectral decay factor κ0 for the EUROSEISTEST array. Site conditions range from soft sediments to hard rock over 14 surface and 6 downhole accelerographs. First, we separate local and regional high-frequency attenuation and measure κ0. Second, we use the existing knowledge of the geological profile and material properties to correlate κ0 with different site characterisation parameters (Vs30, resonant frequency, depth-to-bedrock). Third, we use our results to improve our physical understanding of κ0. We propose a conceptual model comprising two new notions. On the one hand, we observe that κ0 stabilises for high Vs values; this may indicate the existence of regional values for hard rock κ0. If so, we propose that borehole measurements may be useful in determining them. On the other hand, we find that material damping may not suffice to account for the total measured attenuation. We propose that, apart from damping, additional site attenuation may be caused by scattering from small-scale profile variability. If this is so, then geotechnical damping measurements may not suffice to infer overall crustal attenuation under a site; but starting with a regional (borehole) value and adding damping, we might define a lower bound for site-specific κ0.*

***Keywords:*** *high frequencies, attenuation, downhole array, strong ground motion.*

**Περίληψη**

*Στην παρούσα μελέτη υπολογίζουμε την παράμετρο απόσβεσης στις υψηλές συχνότητες, κ0, για το δίκτυο EUROSEISTEST. Οι εδαφικές συνθήκες στους 14 επιφανειακούς και 6 υπόγειους επιταχυνσιογράφους κυμαίνονται από μαλακές αποθέσεις έως σκληρό βράχο. Πρώτα διαχωρίζουμε την τοπική από την περιφερειακή απόσβεση και υπολογίζουμε το κ0. Έπειτα, χρησιμοποιούμε την υπάρχουσα γνώση του εδαφικού προφίλ και των δυναμικών εδαφικών ιδιοτήτων για να συσχετίσουμε το κ0 με διάφορες γεωτεχνικές παραμέτρους (Vs30, συχνότητα συντονισμού, βάθος έως το βραχώδες υπόβαθρο). Τέλος, χρησιμοποιούμε τα αποτελέσματά μας για να βελτιώσουμε τη φυσική κατανόηση του κ0. Προτείνουμε ένα μοντέλο που περιλαμβάνει δύο καινοτόμες ιδέες. Αφ' ενός, παρατηρούμε πως οι τιμές του κ0 σταθεροποιούνται για υψηλές τιμές Vs, κάτι που πιθανώς σημαίνει πως οι τιμές κ0 συγκλίνουν ανά περιοχή για σκληρό βράχο. Σε αυτήν την περίπτωση, προτείνουμε τη χρήση δεδομένων από όργανα εντός γεωτρήσεων για τον υπολογισμό τους. Αφ' ετέρου, παρατηρούμε πως η εδαφική απόσβεση δεν επαρκεί για να περιγράψει τη συνολική μετρηθείσα απόσβεση. Προτείνουμε την ύπαρξη*



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*μιας επιπλέον πηγής απόσβεσης πέραν της εδαφικής: την απόσβεση διασποράς που οφείλεται στις μικρής κλίμακας ετερογένειες του εδαφικού προφίλ. Σε αυτήν την περίπτωση, οι γεωτεχνικές μετρήσεις της απόσβεσης των υλικών ενδέχεται να μην επαρκούν για την εκτίμηση της συνολικής τοπικής απόσβεσης. Ξεκινώντας όμως από μια εκτίμηση της απόσβεσης της περιοχής (από γεώτρηση), και προσθέτοντας την απόσβεση του υλικού, μπορεί κανείς να προσδιορίσει μία ελάχιστη τιμή για το κ0.*
***Λέξεις κλειδιά:*** *υψηλές συχνότητες, απόσβεση, κατακόρυφο δίκτυο, ισχυρή εδαφική κίνηση.*

## 1. Introduction

At high frequencies, the acceleration spectral amplitude decreases rapidly; this has been modelled with the spectral decay factor κ (Anderson and Hough, 1984). Its site component, κ0, is used widely today in ground motion prediction and simulation, and numerous approaches have been proposed to compute it (Ktenidou *et al.*, 2014). Above a given frequency, the amplitude of the Fourier acceleration spectrum (FAS) decays linearly if plotted in linear-logarighmic space. κ is then related to the slope of this line as follows:

$$\kappa_r = -{}^{\lambda}/_{\pi} \tag{1}$$

Measured κr values at a given station scale with distance. The zero-distance intercept of the κ trend with distance (denoted κ0) corresponds to the attenuation that S waves encounter when travelling vertically through the geological structure beneath the station. The distance dependence corresponds to the incremental attenuation due to predominantly horizontal S-wave propagation through the crust. As a first approximation, the distance dependence may be considered linear and denoted by κR, so that the overall κ can be written as follows, in units of time:

$$\kappa_r = \kappa_0 + \kappa_R \cdot R \quad (s) \tag{2}$$

We choose a site marked by complex surface geology, where records are available from a variety of geological conditions ranging from soft soil to hard rock, and where the geometry and dynamic properties of the formations are well known through extensive geotechnical and geological surveys. This will allow us to perform three tasks: 1. Estimate κ0 at stations of varying site conditions. 2. Correlate our κ0 estimates with parameters used in site characterisation (Vs30, depth to bedrock, resonant frequency). 3. Use results to better understand the physics of κ and κ0, particularly with respect to its relation with damping and its values for hard rock.

## 2. Study area and data

The area under study is the Mygdonia basin (Northern Greece), an elongated graben between lake Langada and lake Volvi bound by active normal faults. Over the past two decades, the area has undergone extensive studies in terms of geological structure and soil properties as well as seismic site response; see e.g. Manakou (2007) and references therein. A permanent accelerometric network named EUROSEISTEST (Pitilakis *et al.*, 2013; http://euroseis.civil.auth.gr) has been installed around the basin centre, comprising 14 surface and 6 downhole receivers. The surface layout of the array has the shape of a cross, extending in two directions, perpendicular and parallel to the basin axis (Figure 1). The stations have been installed in different formations to sample ground motion in various geological conditions (Figure 2). They range from very soft, deep valley deposits (TST-000 station at the valley centre) to weathered rock outcrop (PRO-000 and STE stations on the neighbouring hills) and very hard rock (PRO-033 and TST-196 downhole stations).

We use a dataset of 84 earthquakes, recorded by the surface and downhole stations of the permanent network over 13 years. Their moment magnitudes range from 2 to 6.5, with distances out to 150 km. All events are crustal, with depths down to 15km (Figure 3).



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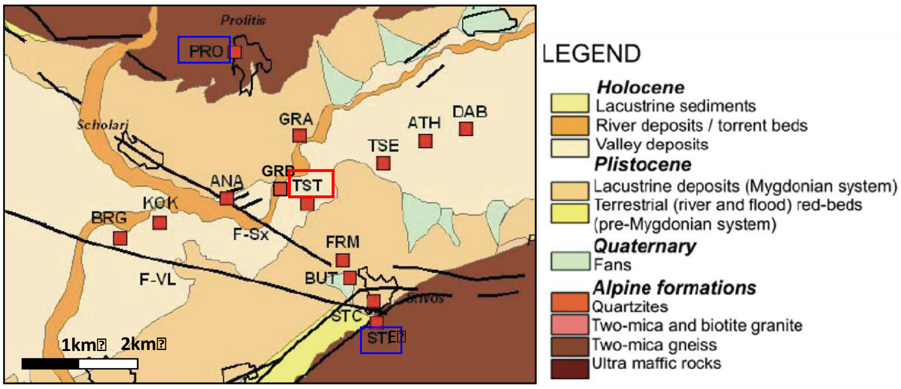
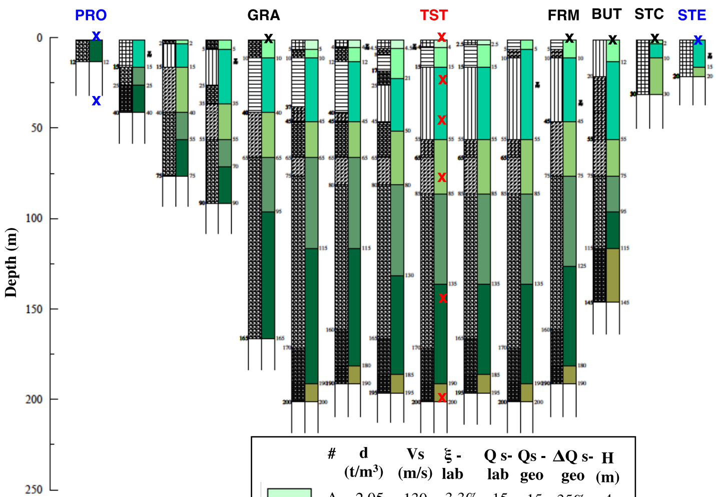



**Figure 1 – Layout of the EUROSEISTEST array – plan view (adapted from Manakou *et al.*, 2010).**




| | # | d (t/m$^3$) | Vs (m/s) | ξ - lab | Q s- lab | Qs - geo | ΔQ s- geo | H (m) |
|---|---|---|---|---|---|---|---|---|
| | A | 2.05 | 130 | 3.3% | 15 | 15 | 35% | 4 |
| | B | 2.15 | 200 | 2.5% | 20 | 20 | 30% | 11 |
| | C | 2.07 | 300 | 1.7% | 30 | 30 | 33% | 40 |
| | D | 2.10 | 450 | 1.3% | 40 | | | 30 |
| | E | 2.16 | 600 | 0.8% | 60 | | | 50 |
| | F | 2.20 | 700 | 0.7% | 70 | | | 55 |
| | G* | 2.50 | 1250 | 0.5% | 100 | | | 10 |
| | G | 2.60 | 2500 | 0.2% | 200 | | | - |

**Figure 2 – Layout of the EUROSEISTEST array - cross-section (adapted from Pitilakis *et al.*, 1999).**



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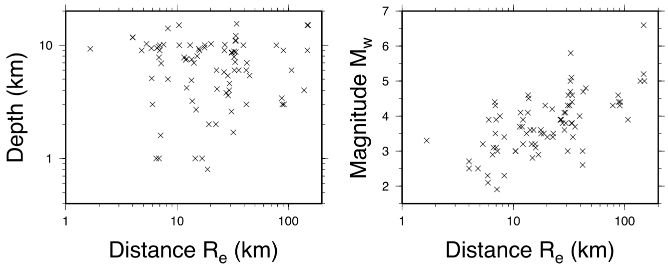


**Figure 3 – Moment magnitude and depth of events versus epicentral distance.**

## 3. Kappa estimation

We apply the classical approach after the definition of Anderson and Hough (1984), now called the ‘acceleration spectrum’ (AS). We measure κ on the acceleration spectrum of individual records at various distances from the site, and then extrapolate to zero-distance to derive the site κ0. We compute the Fourier amplitude spectrum for the S-window and pick frequencies f1 and f2 between which the spectral acceleration amplitude decreases linearly in lin-log space. We follow the steps proposed in Ktenidou *et al.* (2013), and for a more detailed description of the procedure the reader is referred to that work.

Figure 4 shows the picking of f1 and f2 and the computation of κr for an earthquake recorded at all stations of the TST borehole. The results are shown with depth, starting from TST-000, the centre of the basin where Vs30=175 m/s, down to TST-196, the downhole bedrock station where Vs30>1500 m/s (see Figure 1). As expected, the computed κr values differ greatly, with κr at depth being less than half the surface κr. We now have pairs of values for κr and distance for all records (Figure 5). κr values are correlated with the site conditions; data from station TST-000 (blue points) lie above data from TST-196 (red points); however, the scatter is large. There is also an increase of κr with epicentral distance after 15 km. We compute a common κR (see eq. 2) using data from all the stations together, and then estimate of κ0 separately for each individual station, given their different site conditions. The regression results are shown in Figure 5 for stations TST-000 and TST-196.

Our regression yielded a value of κR~0.00048 s/km in the frequency range about 15-35 Hz. Assuming an average crustal shear wave velocity of β=3.5 km/s, this corresponds to a frequency-independent regional Q of 590. This is a relatively low value, especially at such high frequencies.

## 4. Correlation with site characterisation parameters

In this section we make use of the extensive geological, geophysical, and geotechnical studies already conducted at EUROSEISTEST to correlate κ0 with the main parameters used in site characterisation and response. Often, when there is not enough data to measure κ0, empirical correlations are used to infer it. These are made primarily with Vs30, such as those introduced by Silva *et al.* (1998). In Figure 6 (top) we see a positive correlation with a coefficient of R2=47%. If we did not include downhole data, the correlation would decrease to R2=25%. Most existing correlations with Vs30 have even lower coefficients. Given the lack of hard rock surface stations, we propose that downhole data could provide valuable information for κ0 at higher Vs values.

However, it is evident that there is a large scatter in κ0 values. We now look at the correlation of κ0 with fres and Hbed (depth to bedrock, where by bedrock we mean formations G/G* of Figure 2), in Figure 6 (bottom). The correlation coefficients are again of the order of 40-50%. This indicates that κ0 is also correlated with the deeper structure to a similar degree as with Vs30. This is expected, since it is considered to relate to several hundreds of meters beneath a site. We then propose that



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correlations with indices of deeper geology can be used to complement the classical correlations with Vs30.

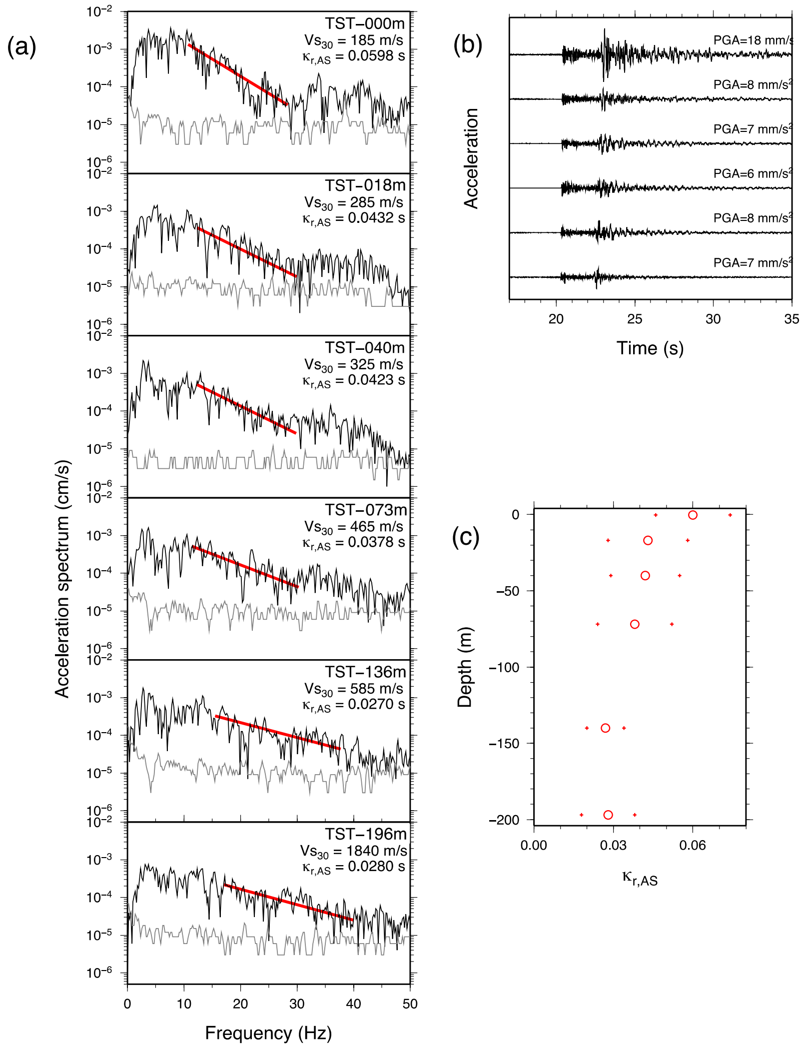


**Figure 4 – a. Example of picking f1 and f2 and κr, AS measurement for an event recorded at all stations in the TST borehole. Noise spectrum plotted in grey, S-window in black, κ fit in red. b. The time histories of the records. c. The distribution of measured κr, AS values (±1 standard error) with sensor depth.**



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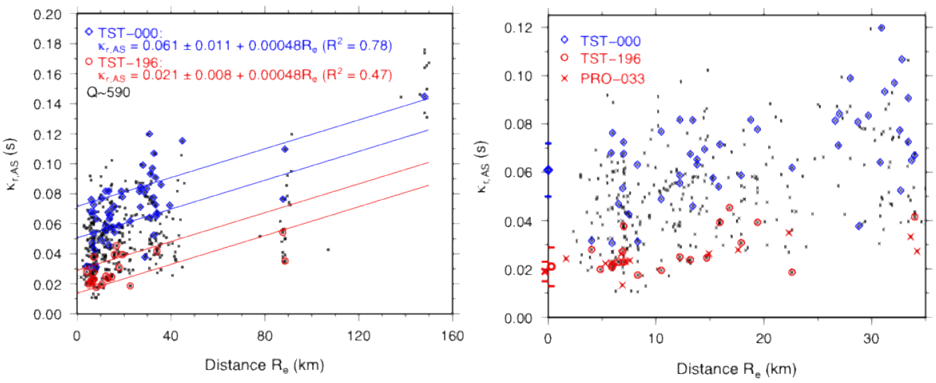


**Figure 5 – a. Individual κr, AS measurements with distance for TST000 (blue), TST-196 (red), and all other stations (black). The lines show the regression results for TST-000 and TST-196, ±1 standard deviation. b. Individual κr, AS measurements out to 35 km, for all stations (black crosses), for TST-000 (blue diamonds), for TST-196 (red circles), and for PRO-033 (red crosses).**

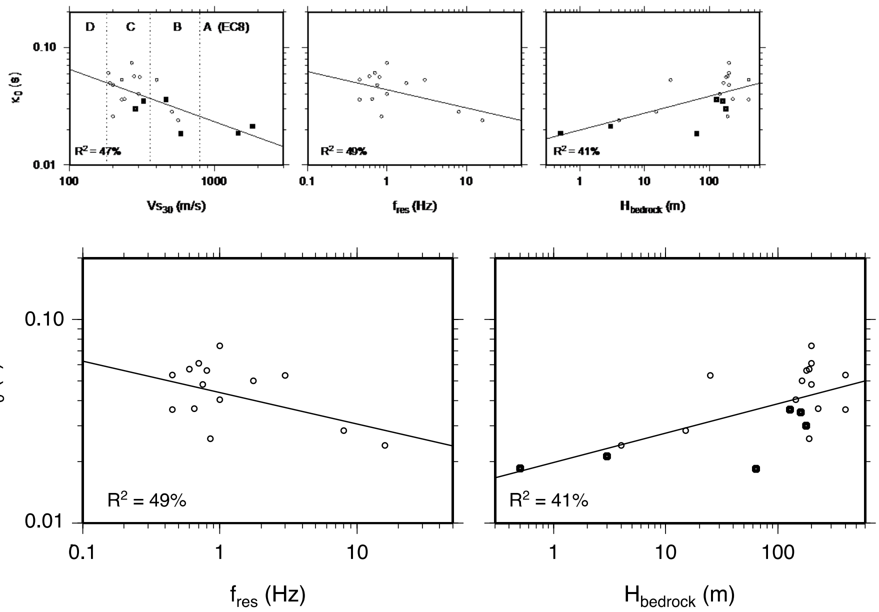


**Figure 6 – Top: Correlation of κ0, AS values with Vs30 (top), resonant frequency (bottom left) and depth to bedrock (bottom right). Dotted lines indicate limits between EC8 site classes A through D. Downhole values are shown as squares and surface values as circles.**



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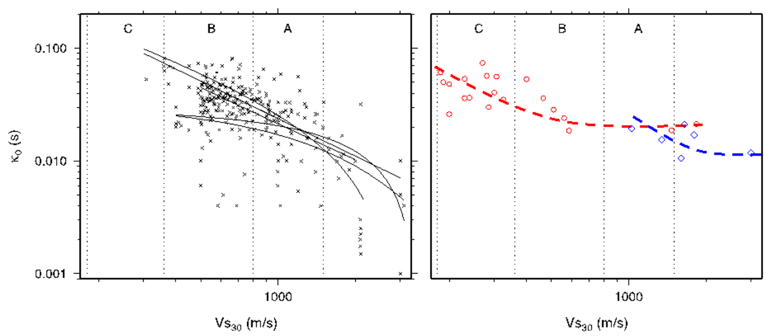


**Figure 7 – Left: Existing data and correlations from literature, all suggesting a downward tendency for hard rock. Right: The alternative asymptotic functional form based on data from Euroseistest (red) and Switzerland (blue), following the AS measurement method.**

## 5. A new conceptual model for κ0

### 5.1. Regional asymptotic values of κ0

As seen in Figure 7 (left), there are very little data available in literature for high Vs30, and the functional forms proposed are very poorly constrained above 1500 m/s. For very hard rock, the question arises: what is the minimum value of κ0? For the sites in our region, we have shown (Figure 6) the downward trend we observed is mainly due to site classes B and C. If we focus on results on rock alone, our data show no significant decrease of κ0 beyond Vs30=550 m/s. So an alternative interpretation to the classic functional form would be that κ0 first decreases as the material hardens, but then reaches an asymptotic value for rock. This type of interpretation also draws from the observation in Figure 5b, in which the short-distance measurements of κr at TST-196 and PRO-033 are indistinguishable, indicating common attenuation properties for the baserock material in the region.

We illustrate this tendency for stabilization at EUROSEISTEST in Figure 7 (right, red). In the same figure (blue) we include results of Edwards *et al.* (2015) for Swiss rock sites, using the same κ approach in roughly the same frequency range (15-30 Hz). In that case too, κ0 seems to stabilise at high Vs30 (>1600 m/s). The asymptotic values are about 21ms for Volvi and 12ms for Switzerland. Given the consistency in measurement method and frequency range, we propose that the difference in the high-Vs30 asymptotic κ0 values might be a regional characteristic of the rock. Figure 8 shows a conceptual physical model describing this. At rock level, the asymptotic κ0 value is determined by the nature of the crust in the region (regional structure of the crust, e.g. Vs, Q, fracturation) and regional source characteristics (e.g., the upper frequency limit to the energy emitted by a source, etc.). As sedimentary layers are added to the rock base (i.e., as we move left on the Vs axis), κ0 increases due to this additional ‘deeper site’ attenuation, probably due to intrinsic damping from the deeper layers. Finally, adding near-surface soil layers to the profile, the additional ‘shallow local’ attenuation leads to the final value of κ0 measured at the surface, including damping and scattering from the top layers. Moreover, the attenuation in the uppermost layers might be affected by non-linear behaviour under high-level excitations.

### 5.2. Scattering as a site attenuation mechanism

In the field of exploration seismology, it is well known that wave propagation through fine layering can filter out high frequencies and may increase the apparent attenuation through short period multiples (O' Doherty and Anstey, 1971), an effect referred to as stratigraphic filtering. However, current discussions on the nature of κ0 do not explicitly include the contribution of scattering. We start from the definition of κ0 as travel time along the vertical propagation path in the last few km:



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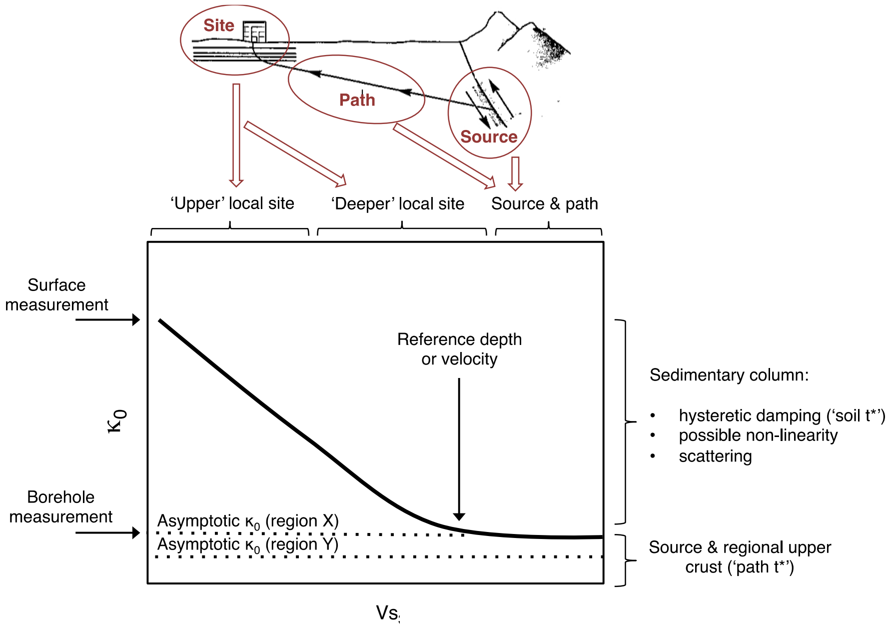


**Figure 8 – Example illustration of the possible regionalization of κ0 and description of the suggested underlying model. We propose an asymptotic κ0 value for very high Vs, which will depend on the source and regional upper crust (dotted lines). The cartoon (Kramer, 1996) illustrates the contribution of source, path, deeper and shallower site components to κ0.**

$$t^* = \int_{path} \frac{dr}{V_s(z)Q(z)} = \sum_{i=1}^{N} \frac{H_i}{V_{si}Q_i} = \kappa_0 \qquad (3)$$

At EUROSEISTEST, we know the soil profile, the Vs and soil damping (i.e., shallow Q) values. We have both geotechnical (lab) and geophysical (site) measurements of the damping, which agree well, so that the uncertainty in the shallow Q is less than 50%. Based on the known profile we can examine the relation between damping and κ0 in our data. We focus on the borehole TST, and start with the measured downhole κ0 value at 196m (κ0DH). Then by adding the borehole-to-surface t*, we predict κ0 at the surface (κ0SUR). In Figure 9 we plot κ0DH=21ms at TST-196 as a starting point on the diagonal. Assuming that Q and Vs are constant and frequency-independent in each overlying layer, we add t* (from equation 31) for each station in between. We predict a mean κ0SUR=36ms at TST-000. The measured surface value is 61±11 s. So moving towards the surface, the starting point does not move along the diagonal (following the arrow), as it would if κ0 were accounted for entirely by t*. Instead, it moves to the right, since measured κ0 is larger than predicted. This discrepancy is Δκ0=25ms, which is significantly larger than the κ0 measurement uncertainty. It is also not due to Q measurement errors (see red shaded area). We propose the discrepancy is due to the additional effect of scattering.



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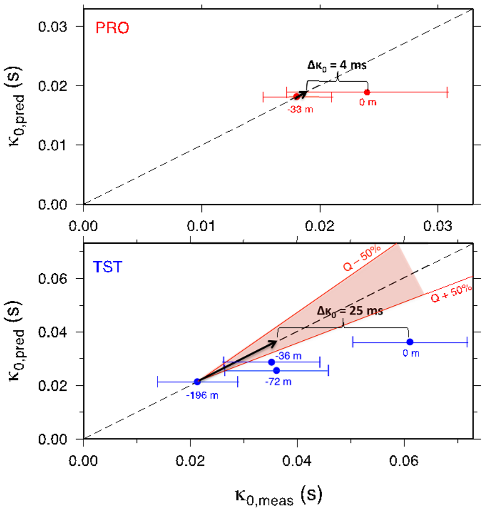


**Figure 9 – Predicted vs measured κ0 values for each station in the TST borehole (stations with more than 10 records). For the deepest downhole station the data points start on the diagonal. Nearing the surface, they move away from it, as measured κ0 becomes larger than predicted. The error bars show uncertainty in κ0 measurement. The light circles mark the final predicted κ0 at the surface. Δκ0 is measured between the measured and predicted surface κ0 values. The shaded red area represents the epistemic uncertainty in predicted κ0 due to Q uncertainty, computed for a 50% shift in Q over the entire profile.**

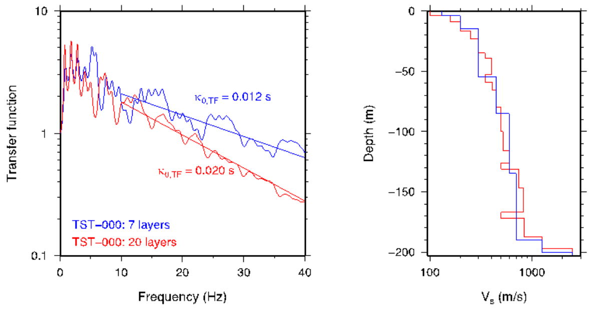


**Figure 10 –Transfer functions (left) at the surface (TST-000) with respect to the bedrock (TST-196) for 1D simulations performed on the profiles on the right: the 7-layer (blue) and the 20-layer profile (red). The increase in profile complexity leads to an increase in κ0, TF.**

At TST, the soil profile is very complex, due to numerous thin deposited near-surface layers. The borehole logging shows over 20 geological units, later simplified to produce the model of Figure 2. This important small-scale inhomogeneity of the profile may cause additional high-frequency attenuation through scattering through two mechanisms; multiple reflections of the upgoing waves; and the forward scattering of energy in the time history. This implies that the measured κ0SUR is the sum of intrinsic material attenuation and scattering, and that the former is accounted in the predicted κ0 while the latter may not be. We test our assumption by forward 1D modelling. We



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compute the site response of the TST soil column for the 7-layer profile of Figure 2, and for the 20-layer profile of Raptakis *et al.* (1998). We use the reflectivity method to compute the theoretical 1D transfer function between the surface and the bedrock. We measure κ on the transfer functions of the two models and find that by increasing the profile complexity, t* increases from 12ms to 20ms, i.e. by 8ms (Figure 10). So adding a few layers to the profile has led to additional attenuation with respect to damping, which we believe may be related to wave reflections and scattering. The actual profile could yield higher attenuation, if one considers more layers and more small-scale velocity inversions. We propose that the stratigraphic filtering effect, previously considered only in the exploration context, should also be taken into account in the context of seismic hazard. The possibility that κ0 comprises a scattering component, which is typically not discussed in hazard studies, should be. If our interpretation stands, it would entail that knowledge of ξ (or Q) for the surface layers may help compute a lower bound for κ0, which however may be higher if there is significant small-scale variability causing scattering in the profile.

## 6. Acknowledgments

Accelerometric, geophysical, and geotechnical data for EUROSEISTEST can be downloaded at: http://euroseisdb.civil.auth.gr (last accessed June 2015). The research was funded by EDF (Electricité de France) project SIGMA. Signal processing benefited from SAC2008 (http://www.iris.edu/software/sac) and some figures were made using Generic Mapping Tools v. 3.4 (www.soest.hawaii.edu/gmt).

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